Demonstration of a Novel Man-Portable Magnetic STAR Technology for Real Time Localization of Unexploded Ordnance

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***Abstract*- We report results of field tests of the first prototype of a novel man-portable Magnetic Scalar Triangulation and Ranging (STAR) technology. The new magnetic sensor system technology is being developed with support from the Strategic Environmental Research and Development Program (SERDP) to provide an easily deployable magnetic sensor system for real-time, point-by-point Detection, Localization and Classification (DLC) of magnetic targets such as Unexploded Ordnance (UXO) and buried mines. The STAR technology is based on a multi tensor gradiometer approach that uses magnetic gradient tensor magnitudes, i.e., "gradient-contraction-type" parameters to perform DLC of magnetic targets. The magnetic STAR sensor uses the scalar functions to triangulate a magnetic UXO-type target's position vector and to calculate the target's magnetic signature vector. The vector components of an object's magnetic signature provide a basis for real time classification of its type, i.e. UXO-like or not.**

In order to provide proof of principle of the STAR concept and demonstrate its advantages for high mobility magnetic sensing applications, we designed, constructed and field-tested a prototype man-portable STAR Gradiometer. The portable gradiometer's hardware and software are completely self- contained and provide a practical and user friendly capability for real time DLC of magnetic targets. Target DLC parameters: e.g., range, bearing, elevation and magnetic signature are correlated with Global Positioning System time and position data and displayed in near real time (total delay < 3 seconds) on a heads-up display that clips onto the operator's safety glasses. Interactive software controls data acquisition, performs signal processing to remove residual motion noise effects and runs the STAR Algorithm to generate and display the target's DLC parameters.

Field tests have demonstrated proof-of-principle of the STAR concept and conclusively demonstrated that the technology has unique advantages for DLC by highly mobile sensing platforms. While being carried and operated by a single individual, the portable sensor has demonstrated very robust, motion noise resistant performance even while undergoing rotational motion of more than 40 degrees per second. The field test results very strongly indicate that the man-portable STAR technology can provide a wide variety of highly maneuverable sensing platforms (including Autonomous Underwater Vehicles) with uniquely effective, motion-noise-resistant magnetic sensing modalities for DLC of magnetic targets such as UXO and underwater mines.

I. Introduction

There is a continuing need for improved magnetic sensor system technologies that can be used by highly mobile sensing platforms (i.e. Autonomous Unmanned Vehicles, Divers, etc.) to perform Detection, Localization and Classification (DLC) of magnetic objects such as underwater mines. In particular there is a heretofore unmet need for a man-portable magnetic sensor system that can be used to perform more effective DLC of Unexploded Ordnance (UXO) such as bombs, artillery shells and buried mines. Therefore, in 2006 and 2007 the Strategic Environmental Research and Development Program (SERDP) has been supporting development of a novel and potentially very valuable man-portable magnetic sensor technology for real-time, point-by-point DLC of UXO. In order to perform true point by point localization and classification of a magnetic dipole target, at every point (within the sensor-target DLC range) a mobile magnetic sensor system must be capable of determining "on the fly" six unknowns; namely three components of vector position ($\boldsymbol{r}$) and three components of magnetic signature ($\boldsymbol{M}$). (The $\boldsymbol{M}$-vector correlates with the size and shape of magnetic UXO, thus measurements of M can be used to classify a magnetic target.) The present development of a portable technology for true real time point by point determination of $\boldsymbol{r}$ and $\boldsymbol{M}$ from sensing platforms in arbitrary, unconstrained motion is based on a multi tensor magnetic "Scalar Triangulation and Ranging (STAR)" concept [1,2] that specifically was created to provide an improved, more motion noise resistant magnetic sensing technology for highly mobile sensing platforms. In particular, Reference [2] describes a prototype man-portable STAR sensor that was designed and constructed (at Naval Surface Warfare Panama City (NSWC PC)) to experimentally determine the validity and effectiveness of the STAR technology concept. In 2007 ongoing field tests of the portable sensor system have conclusively demonstrated the unique advantages of the STAR technology for real time DLC of magnetic targets. The results also indicate that the prototype STAR sensor represents an exceptionally valuable magnetic sensor system technology with many very important military and commercial applications.

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References [1] and [2] respectively provide more details of the basic STAR concept and the construction of the prototype STAR sensor. Therefore, on continuation this paper will only summarize STAR sensor theory and the man-portable sensor's construction details and focus on the results from field tests of the new technology.

II. STAR SENSOR: THEORY AND CONSTRUCTION

To date, development of the STAR technology has concentrated on the DLC of magnetic targets whose signature can be characterized as a magnetic dipole. In particular, the "first generation" STAR concept is based on the following:

- The magnetic dipole equation for the magnetic anomaly field $\boldsymbol{B}_A(\boldsymbol{r}, \boldsymbol{M})$ that emanates from a magnetic target:

$$\boldsymbol{B}_A(\boldsymbol{r}, \boldsymbol{M}) = (\mu/4\pi)[\,3(\boldsymbol{M}\bullet\boldsymbol{r})\boldsymbol{r}/r^5 - \boldsymbol{M}/r^3]. \quad (1)$$

  Where "$\boldsymbol{r}$" is the target's location vector, "$\boldsymbol{M}$" its magnetic dipole moment and μ is the magnetic of the surrounding media (typically $\approx 4\pi \times 10^{-7}$ Tm/A for non-magnetic media).
- The gradient of the target's field ($\boldsymbol{G} = \nabla\boldsymbol{B}$) is a tensor whose components (G_{ij}) are given by:

$$G_{ij} \equiv (\nabla\boldsymbol{B}_A)_{ij} \equiv \partial B_i/\partial r_j = -3\,(\mu/4\pi)\,[\boldsymbol{M}\bullet\boldsymbol{r}(5r_ir_j - r^2\delta_{ij}) - r^2(r_iM_j + r_jM_i)]\, r^{-7}\,. \quad (2)$$

- The magnitude (C_T) of $\boldsymbol{G}$ is a rotationally invariant (hence, motion-noise-resistant) scalar quantity. Specifically, $C_T = |\boldsymbol{G}|$ = the square root of the sum of the components squared of $\boldsymbol{G}$ (i.e., the square root of the "tensor contraction" of $\boldsymbol{G}\bullet\boldsymbol{G}^{\text{transpose}}$),

$$C_T = [\Sigma\,(G_{ij})^2]^{0.5}. \quad (3)$$

- The relation between C_T, r and M can also be written in a form that's analogous to that of a rotationally invariant and robust central-potential-type scalar function; namely:

$$C_T = k(\mu/4\pi)M/r^4 \quad (4)$$

  where "k" is a number that varies from about 7.3 for field points aligned with the target's dipole axis to 4.2 for points transverse to the dipole axis. The C_T scalars have the following characteristics that confer the magnetic STAR approach with improved capabilities for mobile sensing platforms:
- C_T is a rotationally invariant quantity that does not depend on sensor platform orientation. Thus C_T is resistant to motion noise. Contours of C_T = constant form a family of concentric spheroidal "equipotential" type surfaces that are centered on a magnetic target.
- For a given value of k, differences in C_T-values relate only to differences in r-values between the target and the respective C_T-measurement points. Thus for a multi tensor STAR gradiometer array:

a) The distances between C_T-measurement points constitute "triangulation baselines" that are determined by the geometrical design of the gradiometer.
b) The triangulation baselines, their respective end-point C_T values and (4) can be used in a simple algorithm to determine r.
c) Substitution of r-components into gradient equations (2) immediately yields the vector components of $\boldsymbol{M}$ that are so important for UXO discrimination and clutter rejection [3].

Fig. 1 summarizes the STAR concept's mathematical and geometrical bases and describes the general operation of a STAR sensor. Fig. 2 shows the basic configuration of the man-portable sensor system embodiment of the STAR.

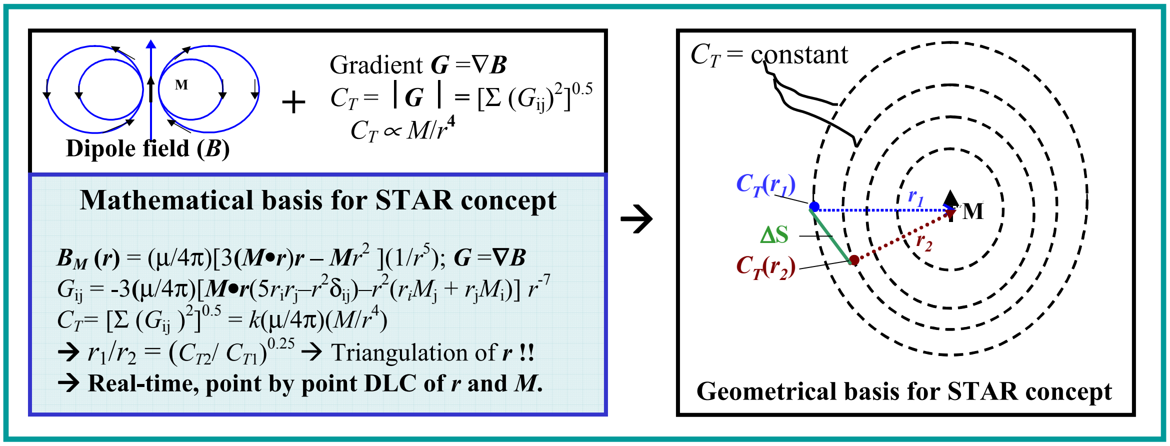

Fig. 1. Summary of the Scalar Triangulation and Ranging (STAR) Concept.
- An array of vector magnetometers simultaneously measures a target's magnetic dipole field $\boldsymbol{B}_M(\boldsymbol{r})$.
- A system processor calculates magnetic gradient tensors ($\boldsymbol{G}_i = \nabla_i \boldsymbol{B}$) and the tensors' contractions ($C_T = [\Sigma (G_{ij})^2]^{0.5}$) at six spatially separate points (i) within the sensor array.
- Gradient contractions ($C_T = [\Sigma (G_{ij})^2]^{0.5} = k(\mu/4\pi)Mr^{-4}$) constitute central potential-type scalar fields that are robust, rotationally invariant and centered on magnetic targets ($\boldsymbol{M}$).
- The STAR Algorithm uses ratios of C_T-parameters to triangulate target location vector $\boldsymbol{r}$, then the XYZ components of $\boldsymbol{r}$ are used to calculate XYZ components of magnetic signature $\boldsymbol{M}$.
- The new STAR technology achieves uniquely effective real-time, point by point Detection, Localization and Classification/ Discrimination (DLC) of magnetic UXO and other targets of interest.

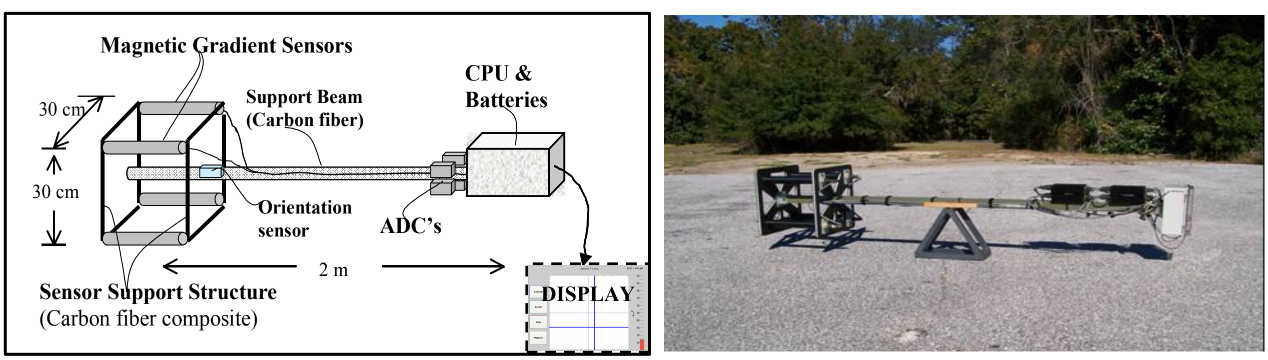

Fig. 2. (a) Sketch of man-portable STAR Gradiometer configuration (not to scale) [2]. Each magnetic gradient sensor is comprised by a set of two parallel Triaxial Fluxgate Magnetometers (TFM) spaced apart by 30 cm. A heads-up display monitor clips onto the operator's safety glasses (not shown).
(b) The prototype Man-Portable STAR Sensor. The sensor system is resting on a triangle with 40 cm sides. For demonstration of the STAR concept, the prototype sensor system was constructed using commercial off the shelf electronics subsystems. As shown in Fig. 3, the prototype STAR sensor is easily portable. However, it is substantially heavier (17 kg) and longer (2.4 m) than a "Mark II" production model will be.

The portable STAR gradiometer contains the following:

- A set of 8 low-noise tri-axial fluxgate magnetometers (TFM) spaced 30 cm apart in a cubic array measures 24 channels of B-field data. Vector B-field data from the sensors in each face of the cube are used to generate a set of six C_T-parameters. The distances (30 cm) between faces of the cube constitute "triangulation baselines" for target-ranging [1,2,4].
- A Sensor Support Structure composed of extremely rigid and lightweight carbon fiber composite supports the TFMs and maintains their alignment in the cubic array.

- A set of 24-bit analog to digital converters (ADC) locked to a Global Positioning System (GPS) receiver convert the TFM's analog signals to digital format that is correlated with GPS timing and position data.
- A triaxial orientation sensor/rate gyro array provides sensor system orientation and acceleration information for reduction of residual gradient imbalance errors.
- A central processing unit /single board computer CPU performs signal processing functions to: a) Calculate 36 gradient channels (one for each cube edge comprised by two TFMs). b) Apply a gradient imbalance/motion noise compensation algorithm to the 36 channels of gradient data. c) Apply a STAR algorithm to calculate target DLC parameters. d) Provide for input/output (I/O) and data storage functions and generate a near real time (within 3 seconds) display of target DLC parameters.
- A heads-up display that clips onto the operators' safety glasses provides a user-friendly indication of DLC parameters and sensor operational mode. A belt-mounted touchpad-type mouse allows an operator to easily control the sensor's operational modes.
- A set of lithium-polymer batteries provides over three hours of electrical power for the sensor system.

III. Results and discussion

Figs. 3-6 of the following discussion of results will also be adapted for presentation in [5]. Fig. 3 shows the basic field test arrangement for demonstrating the portable STAR Gradiometer. As a tensor gradiometer is hand-carried in normal operation with its operator walking at a normal gait, the sensor system's orientation typically may change by tens of degrees per second. Since the magnetic anomaly field of UXO is convolved within the much larger Earth's background field (($\boldsymbol{B}_E$) ≈50,000 nT), a portable gradiometer's vector *B*-field sensing elements typically will be measuring non-target-related field changes on the order of thousands of nT per second. In principle, a perfectly balanced tensor gradiometer will subtract out the common-mode Earth's field and only measure the gradient of the UXO's field. However, in practice all real tensor gradiometers will have some level of imbalances between respective field-sensing channels. The imbalances produce gradient imbalance errors that must be removed from the gradient data or they will cause sensor-orientation-dependent motion noise as the sensor system is moved. Poorly compensated motion noise can obscure the signature of a magnetic target and/or cause false detection alarms that can greatly reduce the effective mobility and effectiveness of a mobile sensor system.

Fig. 3. Man-portable STAR Gradiometer being carried in the vicinity of a simulated target (a 31-cm steel sphere). The black boxes near the Operator's right hand are commercial analog to digital converter (ADC) units. The white box contains the sensor system's CPU, batteries and GPS receiver. The heads-up display unit (not easily visible in the unmagnified photo) is clipped onto the Operator's safety glasses.

For this project, a very effective motion noise compensation method was developed for reducing the effects of gradient imbalance errors. Prior to using the sensor to locate magnetic targets, the operator can select "Calibrate" mode (see Fig. 6) and the sensor measures and calibrates gradient imbalances at multiple points while the operator rotates the sensor system in heading, pitch and roll in a gradient-free region. The sensor's calibration algorithm uses the gradient imbalance measurements to compute a transformation that, when applied to the each gradient sensor's data, will minimize (in a least squares sense) its gradient imbalance errors. The portable sensor develops a total of 12 separate transformations –one for each "edge" of the cubic array. In operation, the precalibrated transformations are applied in near real time to their respective gradient sensing axes. As demonstrated by the data in Fig. 4 (for a single sensing axis), the gradient imbalance compensation approach reduces motion noise to very near the TFM's internal random noise levels.

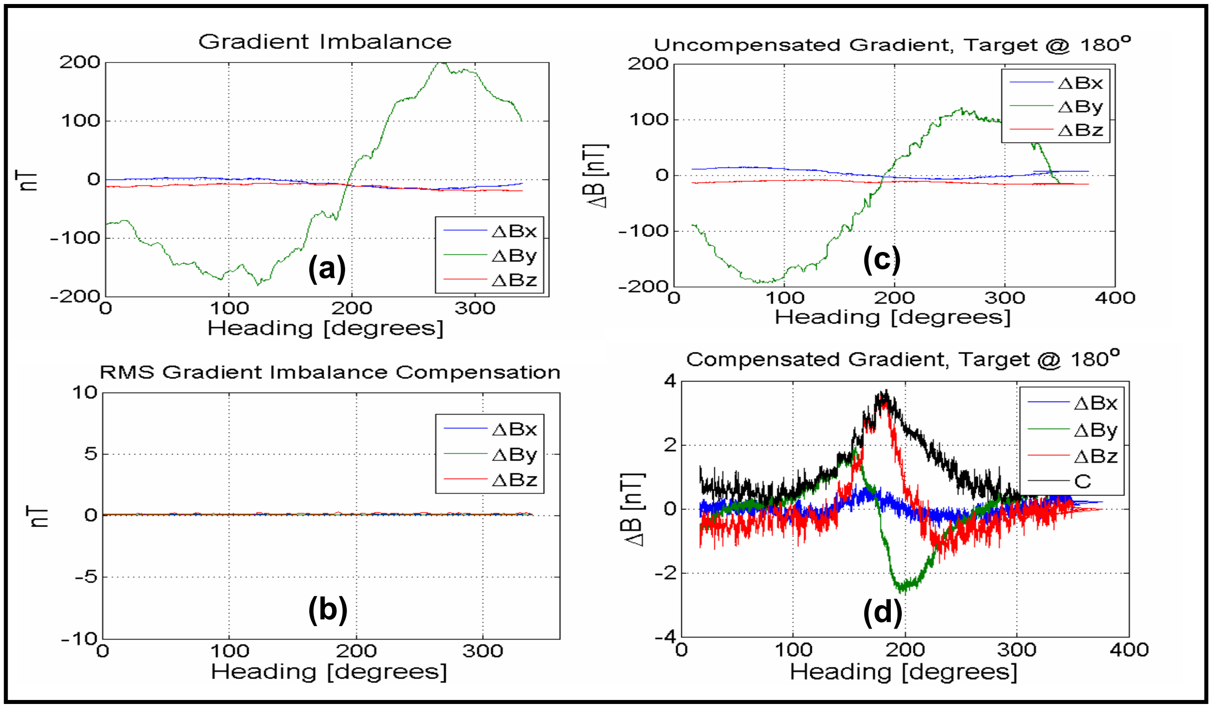

Fig. 4. **Reduction of motion noise effects and enhanced target-discrimination**. The data are from a single -axis gradient sensor comprised by two TFMs, a 6-channel 24-bit ADC and an embedded (PC-104) CPU. All data were taken as the sensor was swung at about 3°/second on a 5-m diameter circular path.

The data curves on the left side represent correlated gradient and orientation data that were taken as sensor heading, pitch and roll were changed in a gradient-free zone. The data curves show: **(a)** Gradient imbalance errors on the order of +/- 200 nT (due to gradient-channel misalignments). **(b)** Gradient data after application of the motion noise compensation algorithm. The motion noise is reduced to the sensors' uncorrelated random noise levels (about 0.25 nT peak to peak).

The data curves on the right side were taken as the single-axis sensor was swung past a 14.5 Am^2 magnetic dipole target located at 180° and at a closest distance of 6.0 m. The data are: **(c)** Uncompensated gradients with the target signature obscured by the sensor's motion noise. **(d)** Motion noise compensated gradients after near real time (< 3 seconds) application of the precalibrated motion compensation algorithm to the data. The algorithm allowed enhanced discrimination of the target gradient signature and accurate calculation of a partial (three-component) gradient contraction *C*-parameter at sensor-target ranges up to 9 m.

While operating in "Locate" mode the portable gradiometer continually performs the following functions: a) Digitization of 24 channels of *B*-field data from 8 TFMs, b) Correlation of digitized data with GPS timing and location, c) Calculation of 36 channels of motion compensated gradient data, d) Calculation (using a STAR algorithm) of target DLC data. e) Storage of all field, gradient, GPS and DLC data on a compact flash memory. f) Display of target DLC parameters (e.g., vector components of target location and magnetic dipole signature). If necessary the operator can select "Playback" mode to rerun the stored data.

Fig. 5 represents a set of compensated gradient (***G***) data and the gradient contraction parameter (C_T) from the TFM sensors in one face of the cubic array. The data were taken as the hand-carried STAR sensor was rapidly rotated at about 40°/second past a 14.5 Am^2 magnetic dipole target. These data demonstrate the portable STAR technology's unique capability for DLC using high mobility sensing platforms. During an hours-long search for UXO the portable sensor system will calculate and store (at about 100 Hz) millions of correlated sets of DLC information and GPS data. For each correlated data set the STAR Algorithm combines data from all six sensor-cube faces to perform DLC operations and, when a target is detected, calculate the vector components of its position ***r*** and its magnetic signature ***M***.

In addition to the STAR technology's unique capability for performance of point by point DLC while the sensor platform is undergoing rapid, non-linear motion it also provides for user-friendly operation wherein the STAR system's tensor arithmetic processes (summarized in Fig. 1) are transparent to the operator. That is, in order to use the STAR technology to localize magnetic targets such as UXO, the operator only needs to select "Locate" mode and carry the sensor in the region to be searched. As shown in Fig. 6, the sensor will automatically provide the operator with an easy to interpret indication of the target's location and magnetic signature. If desired GPS coordinates also can be displayed and/or stored.

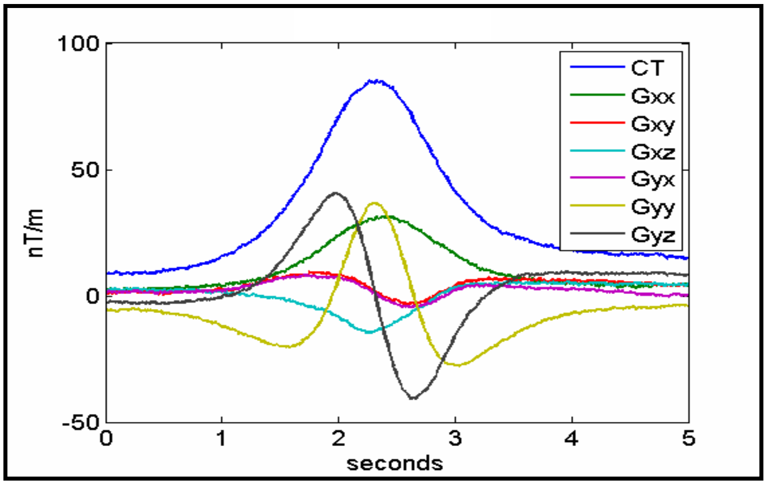

Fig. 5. Demonstration of motion-noise resistance. The data were taken from the TFMs in one face of the sensor cube as the STAR was rapidly swung in a 200° arc past a 14.5 Am^2 dipole target. For each data point the STAR Algorithm processes C_T and Gij data from six sensor-cube faces to generate a near real time (within 3 s) operator-friendly display of target DLC data (e.g., Fig. 6).

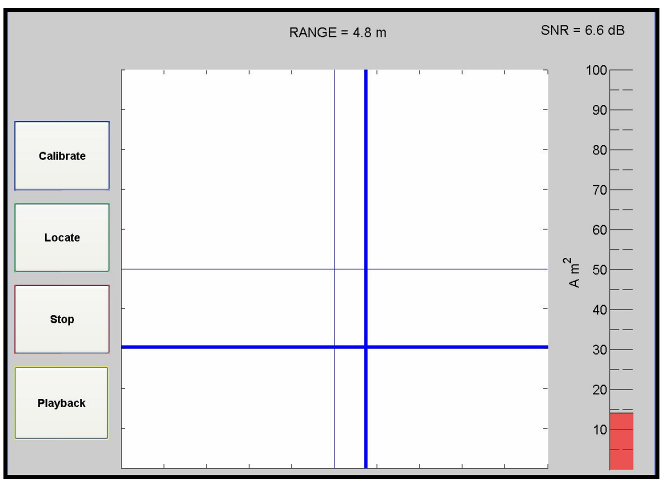

Fig. 6. Screenshot from operator's display. The data were taken as the STAR sensor was hand-carried at a distance of about 5 m from a 14.5 Am^2 dipole target. The blue crosshairs provide a continuously updated indication of the target's bearing and elevation relative to the sensor's longitudinal symmetry axis. A bar graph indicates target magnetic dipole signature. The virtual instrument buttons (Calibrate, Locate, Stop and Playback) and a belt-mounted touchpad type mouse allow the operator to easily control sensor system operation.

Thus far the portable STAR technology's performance has been demonstrated against isolated dipole-type targets. While being hand carried by a single individual, the portable sensor will detect a 14.5 Am^2 magnetic dipole target at ranges of 7 m and at 5 m or less, provide an accurate and robust indication of the target's position and magnetic signature. Following the demonstrations of the validity of the STAR concept and its advantages for real time, point by point DLC, this project has focused on optimization of the sensor system's performance against isolated dipole targets. For example, the effective single-target DLC range is being enhanced. However, the ultimate objective of this R&D effort is to develop a high mobility sensing system that will be capable of discrimination of UXO that is embedded in magnetically complex environments, that is, environments characterized by combinations of multiple overlapping target fields, non-UXO-type magnetic clutter and/or geologic noise.

IV. Conclusion

A novel and very effective man-portable magnetic gradiometer technology for real-time, point-by-point Detection, Localization and Classification (DLC) of magnetic UXO has been demonstrated. Field tests under realistic operating conditions indicate that the magnetic Scalar Triangulation and Ranging (STAR) technology potentially will provide a wide variety of highly

maneuverable sensing platforms (including, Autonomous Unmanned Vehicles and Navy Divers) with uniquely effective, motion-noise-resistant magnetic sensing capabilities for DLC of magnetic targets including Unexploded Ordnance and buried mines.

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REFERENCES

[1] R.F. Wiegert and J. Oeschger, "Generalized Magnetic Gradient Contraction Based Method for Detection, Localization and Discrimination of Underwater Mines and Unexploded Ordnance," MTS/IEEE OCEANS 2005 Conference Proceedings.
[2] R.F. Wiegert and J. Oeschger, "Portable Magnetic Gradiometer for Real-Time Localization and Classification of Unexploded Ordnance," MTS/IEEE OCEANS 2006 Proceedings, September 2006.
[3] T.W. Altschuler, "Shape and Orientation Effects on Magnetic Signature Prediction for Unexploded Ordnance," UXO Forum 1996, (Williamsburg, VA, March 26-28, 1996), Conference Proceedings, pp.282-291.
[4] R.F. Wiegert, US Patent 6,841,994, "Magnetic Anomaly Sensing System for Detection Localization and Classification of Magnetic Objects."
[5] R.F. Wiegert and J. Oeschger, "Man-Portable Magnetic STAR Technology for Enhanced Real Time Localization of UXO" 2007 UXO/Countermine/Range Forum Proceedings, August 27-30, 2007.